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Nature of the scissors mode in nuclei near shell closure: the tellurium isotope chain ☆

E. Guliyev [a], A.A. Kuliev [b], P. von Neumann-Cosel [c], A. Richter [c]

[a] *Department of Engineering Physics, Faculty of Science, Ankara University, Ankara, Turkey*
[b] *Department of Physics, Faculty of Science and Art, Sakarya University, Sakarya, Turkey*
[c] *Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*

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Abstract

Quasiparticle random-phase approximation calculations, where rotational, translational and Galilean invariance are restored selfconsistently by using separable effective forces, are presented for the ground state dipole response in the even-mass isotopes $^{122-130}$Te. The simultaneous description of E1 and M1 transitions permits a direct comparison with nuclear resonance fluorescence experiments. The extracted properties of the scissors mode reveal a considerable complexity in these near closed-shell nuclei: neither approaches successful in deformed nuclei nor a two-phonon picture suggested near shell closures nor the interacting boson model can fully account for the data.

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The orbital magnetic dipole scissors mode has attracted considerable interest as a fundamental excitation of nuclei at low excitation energies [1]. Originally predicted in the two-rotor model [2] and the interacting boson model [3] with proton–neutron degrees of freedom (IBM-2, see [4]) its existence was experimentally proven in high-resolution inelastic electron scattering experiments [5].

In recent years an extensive set of data from high-resolution photon scattering [6] has been obtained covering the whole major shell $N = 82$–126. This data set allows systematic studies of global features of the mode such as the total B(M1) strength and the energy centroid in heavy nuclei. The pronounced strength variation, which was shown to be proportional to the square of the ground state (g.s.) deformation [7,8], has been successfully interpreted in terms of model-independent phenomenological [9,10] and IBM-2 [11] sum rules. For a discussion of microscopic approaches see, e.g., [12–14]. Also the approximate constancy of the mean excitation energy can be reproduced by the phenomenological approach of [10] assuming a close similarity of the moment of inertia and the g-factors to those of the g.s. rotational band. The collective nature of the mode implied by this result is independently

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E-mail address: vnc@ikp.tu-darmstadt.de (P. von Neumann-Cosel).

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confirmed by an analysis of the statistical properties of the level sequences [15].

However, while the global properties are reasonably understood in regions of moderate to large deformations, the nature of the scissors mode is an open question in nuclei near shell closures where the simple geometrical picture of a scissors-like motion of deformed proton and neutron bodies breaks down.[1] There, a two-phonon interpretation seems more appropriate where the scissors mode belongs to the multiplet resulting from the coupling of the lowest isoscalar and isovector (in the language of shell model), respectively, mixed symmetry (in the language of IBM-2) quadrupole vibrations. (For a discussion of the nature of mixed-symmetry states in the dynamical limits of IBM-2 see [16]). Such a two-phonon character is strongly suggested by a detailed comparison of two-phonon and one-phonon decay of the scissors mode for the case of ^{94}Mo [17,18]. It was in fact anticipated in the IBM-2 [19] and complies with the Q-phonon interpretation of the low-energy collective structure of nuclei [20].

In order to see whether such a picture can be generalized we focus on another example provided by the chain of stable tellurium isotopes. Similar to ^{94}Mo these nuclei represent cases with two active particles above a magic number ($Z = 50$). The non-negligible variation of the deformation along the isotopic chain, extracted from the collectivity of the B(E2, $0_1^+ \rightarrow 2_1^+$) transition [21], allows an in-depth test of the above considerations.

The low-energy dipole strength in ^{122,124,126,130}Te has been studied previously at the superconducting Darmstadt electron linear accelerator S-DALINAC with the (γ, γ') reaction [22,23] and compared to calculations with the microscopic quasiparticle phonon model (QPM) in a spherical basis. A two-phonon structure of the scissors mode states is suggested (see [24] for similar calculations on ^{94}Mo). Furthermore, a strong two-phonon E1 transition is expected in the same energy region due to octupole coupling (see, e.g., [25,26]). These calculations overall reasonably describe the data. However, the complex experimental

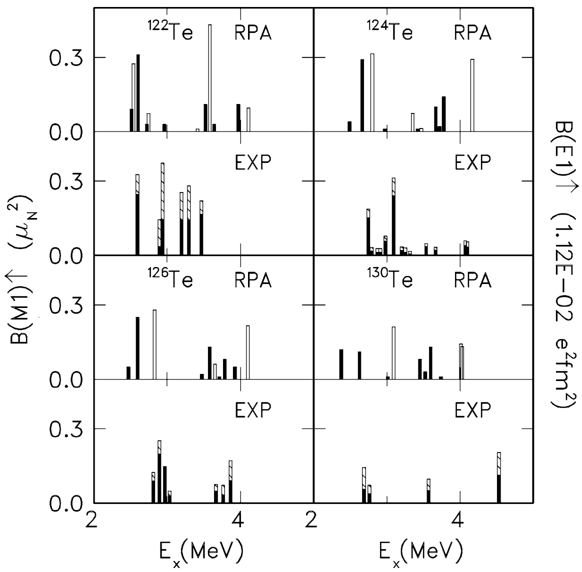

Fig. 1. Experimental dipole strength distributions in ^{122,124,126,130}Te from (γ, γ') experiments [22,23] compared to the QRPA calculations described in the text. Because the parities of most transitions are experimentally unknown, scales for the conversion to B(M1)↑ and B(E1)↑ strengths are given on the left and right side of the figure, respectively. The shaded areas of the bars represent the experimental uncertainties. In the QRPA results, M1 transitions are shown as full bars and E1 transitions as open bars, respectively.

strength distributions displayed in Fig. 1 exhibit much more fragmentation than predicted, indicating that deformation plays a non-negligible role. Thus, the stable even–even tellurium isotope chain exhibits features partially associated with vibrational and partially with (moderately) deformed nuclei.

These observations form the basis for new calculations of the low-energy dipole strength in $^{122-130}$Te in the framework of the quasiparticle random phase approximation (QRPA). Although the underlying assumption of an axially deformed mean field may be questioned, at present it represents the only possible approach to an improved understanding of the fine structure experimentally observed for the dipole modes. The results shown here have been obtained with the model of Ref. [27]. There, by the selection of suitable separable effective isoscalar and isovector forces, rotational invariance is restored for the description of the M1 modes as well as translational and Galilean invariance for the calculation of E1 excitations without introducing additional parameters.

[1] Note that the expression 'scissors mode' is used throughout the text as a synonym for low-energy orbital magnetic dipole strength independent of the particular shape of the nuclei under investigation.

Thus, these results permit a direct comparison with experimental dipole strength distributions deduced from (γ, γ') experiments. Together with the experimental information on possible $J^\pi = 1^-$ candidates from other experiments they provide a guideline to extract the scissors mode strengths and explore its features.

The method of restoring broken symmetries [28] has been applied to calculations of the scissor mode in heavy deformed nuclei, but restricted to the isoscalar part of the quasiparticle Hamiltonian [29]. In the present approach simultanoues restoration is achieved for the isovector part, thus avoiding the problem of the unknown coupling strength of the isovector quadrupole–quadrupole interaction. The method described in Eqs. (2)–(7) of [27] can also be used for a restoration of translational symmetry, i.e., removal of the spurious state, by substituting the linear momentum operator P for the angular momentum operator J. Therefore, we restrict ourselves here to a short description of the application to low-lying E1 excitations.

The calculations were carried out with a Hamiltonian of the form

$$H = H_{\mathrm{sqp}} + h_0 + h_\Delta + W_1, \tag{1}$$

where H_{sqp} is the Hamiltonian for the single-quasiparticle motion and the interactions W_1 represent the coherent isovector dipole vibrations of protons and neutrons, the centre-of-mass (c.m.) of the nucleus being at rest. According to [30] the translational invariance of the single-quasiparticle Hamiltonian can restored with the aid of a separable isoscalar effective interaction of the form

$$h_0 = -\frac{1}{2\gamma} \sum_\mu [H_{\mathrm{sqp}}, P_\mu]^+ [H_{\mathrm{sqp}}, P_\mu]. \tag{2}$$

Here P_μ are the spherical components of the linear momentum for the $J^\pi = 1^-$ excitations, and $\mu = \pm 1$. In order to restore the broken Galilean symmetry of the pairing potentials U_Δ we further add a term in Eq. (1)

$$h_\Delta = -\frac{1}{2\beta} \sum_\mu [U_\Delta, R_\mu]^+ [U_\Delta, R_\mu], \tag{3}$$

where $R_\mu = \sum_{k=1}^{A} r_k Y_{lm}(\Theta_k, \Phi_k)$ is proportional to the c.m. coordinate of the nucleus. The coupling parameters

$$\gamma = \langle 0 | \big[P_\mu^+, [H_{\mathrm{sqp}}, P_\mu] \big] | 0 \rangle$$

and

$$\beta = \langle 0 | \big[R_\mu^+, [U_\Delta, R_\mu] \big] | 0 \rangle$$

are determined by the mean field and pairing potentials, respectively. For the transitional invariant dipole interaction we use the isovector form

$$W_1 = \frac{3}{2\pi} \chi_1 \left(\frac{NZ}{A} \right)^2 \big(\vec{R}_{\mathrm{n}} - \vec{R}_{\mathrm{p}} \big)^2. \tag{4}$$

Here, χ_1 denotes an isovector dipole–dipole coupling constant and $\vec{R}_{\mathrm{n}}$, $\vec{R}_{\mathrm{p}}$ are the c.m. coordinates of the neutron and proton systems, respectively.

The single-particle energies were obtained from the Warsaw deformed Woods–Saxon potential [31]. The basis contained all discrete and quasi-discrete levels in the energy region up to 6 MeV. This results in about one thousand two-quasiparticle spin-1 states for each parity. The continuum spectrum was not taken into account. The model-independent sum rule for the electric dipole matrix elements [30]

$$\sum_{ss'} \big(V_{s'}^2 - V_s^2 \big) (E_s - E_{s'}) r_{ss'}^2 = \frac{9}{4\pi} \frac{\hbar^2}{m} N_\tau, \tag{5}$$

which is independent of the pairing interactions, served as a test of the completeness of the basis. In Eq. (5), E_s and $r_{ss'}$ are the single particle energies and the dipole matrix elements, respectively, V_s denotes the pairing occupation parameter and N_τ is the number of particles with $\tau = p, n$.

For the calculation of dipole transitions in the even–even tellurium isotopes with mass numbers 122–130 the pairing parameters Δ were calculated using the monopole pairing interaction constants given in [32]. The deformation parameters were taken from Ref. [21]. Besides, the model contains a single parameter only for the calculation of either M1 or E1 transitions. For M1 excitations, the isovector spin–spin interaction strength was chosen to $\chi_{\sigma\tau} = 25/A$. This value allows a satisfactory description of the scissors mode fragmentation in well-deformed rare earth nuclei (see [27]). It can be estimated, e.g., from the retardation of magnetic moments of single-particle states [33]. Other QRPA calculations of the scissors mode use slightly larger values [34,35] but these differences are well within the range suggested by a comparison of different approaches (for a discussion see [36]). In the case of E1 excitations a strength parameter

$\chi_1 = 300/A^{5/3}$ MeV fm^{-2} is suggested by Ref. [30] for the isovector dipole–dipole interaction. Its magnitude is related to the isovector symmetry potential and the above value is in close agreement with the analysis of Bohr and Mottelson [33]. A similar value has also been used in QPM calculations of the E1 response in deformed rare earth nuclei [37].

The QRPA results for the g.s. M1 (full bars) and E1 (open bars) transition strengths up to an excitation energy of about 4.5 MeV are displayed in Fig. 1. The agreement with the experimental findings is quite encouraging. In particular, the splitting of the strength into two bumps observed in ^{126}Te at $E_x \approx 2.9$ MeV and $E_x = 3.5$–4 MeV is well reproduced. Also, the calculation accounts for the observation of two well-separated transitions at low energies and a single one around 3 MeV in ^{130}Te. For ^{122,124}Te, the agreement is quite good at excitation energies below 3 MeV, while larger differences are found at higher E_x.

An important conclusion can be drawn with respect to the additional dipole transitions observed in the energy region where the excitation of the two-phonon 1^+ and 1^- states is expected from the QPM calculations. The present results suggest that these largely arise from a fragmentation of the M1 strength while the low-lying E1 strength is almost exclusively concentrated in a single (the two-phonon) state in each nucleus. This finding, together with the information on 1^- candidates available from other experiments (for a discussion see [23]), enables us to extract the total M1 strength in the energy interval $2 \leqslant E_x \leqslant 4$ MeV which is attributed to the scissors mode.

The extracted scissors mode strengths are shown in Fig. 2 as a function of the square of the deformation parameter δ. The error bars correspond to the sums of the individual uncertainties of the experimentally observed transitions. This conservative estimate is taken in order to account for possible unobserved inelastic transitions in the (γ, γ') data and the model dependence of the identification of M1 transitions based on the calculations described above. It may be noted that g.s. E1 and E2 transitions (Refs. [38,39], respectively) were identified in the energy region of interest by (γ, γ') experiments on nuclei close to the $Z = 50$ shell closure. However, the widths of the latter are small compared to the prominent transitions shown in Fig. 1.

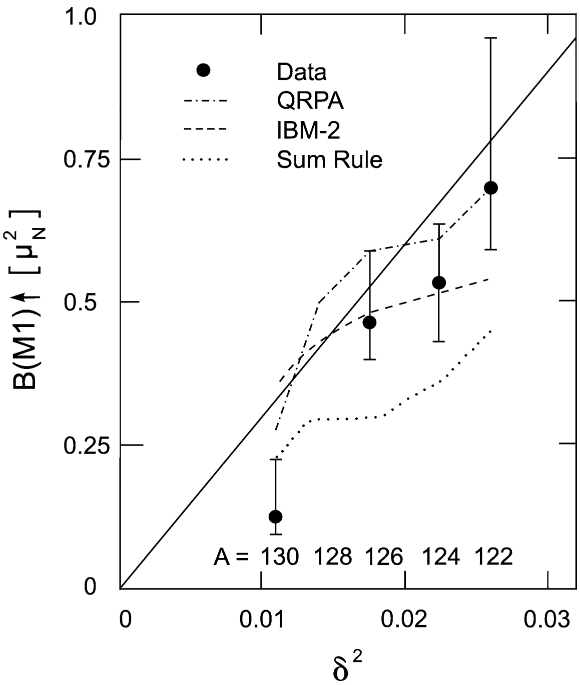

Fig. 2. Summed scissors mode strength in $^{122-130}$Te as a function of the square of the deformation parameter δ. Note that the mass numbers decrease with increasing δ^2. The straight line represents the empirical parametrization of [40]. The dashed-dotted line shows the result of the QRPA calculation described in the text, the dashed line gives the predictions of the $O(6)$ limit of IBM-2 [41], and the dotted line the sum rule approach of Ref. [10].

Contrary to the behaviour in the Sm and Nd isotope chains above the $N = 82$ shell closure [7,8], the mass numbers of the isotopes plotted in Fig. 2 decrease with increasing deformation because the neutron number is above midshell in the $N = 50$–82 valence shell. The results for the more deformed isotopes $^{122-126}$Te are in reasonable agreement with the empirical deformation dependence deduced for the $N = 82$–126 major shell [10,11,40]. As an example, the parametrization of [40] is displayed as a straight line. However, the value for ^{130}Te lies significantly below (note that the rather strong dipole transition to the state at $E_x = 4.531$ MeV is excluded from the analysis).

In the following, various approaches aiming at a systematic description of the scissors mode features are discussed with respect to the data in Fig. 2. The empirical sum-rule analysis of Ref. [10] shown as dotted line leads to too small B(M1) values except for

^{130}Te. Furthermore, the centroid energy is predicted at $E_{\mathrm{x}} > 4$ MeV in contrast to the data. This failure can be traced back to a breakdown of one of the basic assumptions underlying the approach. Obviously, the $g(2_1^+)$ factors in these near closed-shell nuclei no longer serve as a measure of the rotational properties.

The predictions of the IBM-2 sum rule [11] considerably exceed the experimental scissors mode strengths. However, one should be aware that in contrast to the approximation used in [11], the $0_1^+ \to 2_1^+$ transition no longer exhausts a large fraction of the non-energy weighted isoscalar E2 sum rule. The isoscalar E2 strength in these nuclei near shell closure is dominated by the existation of the giant quadrupole resonance, and other low-lying collective E2 transition might contribute as well. This correction should bring the scissors mode strengths deduced from the IBM-2 sum rule in better agreement with experiment, but the experimental information on the g.s. E2 strength distributions is presently insufficient for a quantitative analysis.

Another possibility of interpretation of the data is based on the dynamical limits of IBM-2 where analytical expression have been derived for the scissors mode strength [41]. The transition from the g.s. into the scissors mode state vanishes in the $U(5)$ limit, but similar to ^{94}Mo a description within the $O(6)$ symmetry may be appropriate. The result is displayed in Fig. 2 as dashed line. The δ^2 dependence is much less pronounced than observed in the data, leading to an underprediction for ^{122}Te and an overprediction for ^{130}Te.

There is some debate in the literature whether the even–even Te isotopes (in particular, ^{124}Te) can be interpreted in the $O(6)$ limit (see, e.g., [42,43] and references therein). Detailed fits to the low-energy structure suggest parameters between $U(5)$ and $O(6)$ for $^{122-130}$Te [44,45]. Rikovska et al. [45] also presented results for the energies of the mixed-symmetry 1^+ states. Unfortunately, no results were given for the g.s. M1 transition strengths. IBM-2 calculations with parameters fitted to experimental data may provide a superior description of the systematics in Fig. 2, in particular, reflecting a more vibrational character—and thus reduced B(M1) strength—of the heavier Te isotopes. However, the boson g-factors deduced by [45] present a problem because they differ substantially from the free values suggested microscopically [46] and confirmed by the successful description of the scissors mode in rare-earth nuclei [11] and ^{94}Mo [17]. The B(M1) values corresponding to the two choices differ by a factor of three. In view of the large amount of new spectroscopic data available on the Te isotopes [47] a revised IBM-2 analysis of this problem would be worthwhile.

The QRPA calculations (dashed-dotted line) described above are capable to account for the B(M1) strengths in the more collective $^{122-126}$Te nuclei and slightly overestimate the experimental result for ^{130}Te. It may be noted that the sensitivity of the experiments may allow for unobserved fragmented M1 strength of the order of $\approx 0.05\ \mu_N^2$ (somewhat less for the ^{124}Te experiment). This could partly explain the deviation of ^{130}Te from the global δ^2 dependence. However, the fragmentation of the scissors mode is reduced towards the shell closure [15] which makes the assumption unlikely.

To summarize, we have presented a QRPA approach which allows a selfconsistent calculation of g.s. excitations populating 1^+ and 1^- states after restoration of rotational, translational and Galilean invariance by separable forces. The simultaneous description of M1 and E1 transitions permits a direct comparison with (γ, γ') data selective on dipole transitions, but usually lacking parity information. Despite the deformed single-particle basis the calculations describe the dipole strength distributions in the near closed-shell nuclei ^{122,124,126,130}Te surprisingly well.

With the aid of the QRPA results it is possible to extract the M1 scissors mode strengths in these nuclei and study their deformation dependence. Sum-rule approaches developed to described the systematics of the scissors mode in rare-earth nuclei fail here. Also, a description within IBM-2 cannot reproduce the experimental δ^2 dependence. On the other hand, QPM calculations in a spherical basis provide a reasonable description of the gross properties, suggesting a two-phonon character of the mode near closed shells. However, such calculations cannot account for the experimentally observed fragmentation.

For a deepened understanding of the scissors mode properties in the tellurium isotopes, several aspects require further attention. On one hand, the role of spin contributions needs to be investigated. While the present QRPA results suggest that their mixing with the dominant orbital mode is small, experimental verification is missing. Modern high-resolution experiments with inelastic proton scattering or charge exchange reactions should be able to provide an answer. On the other hand, it would be important to extend the (γ, γ') studies to ^{128}Te and to remeasure ^{130}Te with improved sensitivity in order to firmly establish deviations from the δ^2 dependence when approaching the $N = 82$ shell closure. Within IBM-2, characteristic decay features have been pointed out as a signature of mixed-symmetry 1^+ states [4]. Thus, further spectroscopic studies aiming at an identification of the relevant states and transitions, similar to the well-studied example of ^{94}Mo [17,48], would be of considerable value. Furthermore, an interesting problem in itself is the question to what extent QRPA calculations reflect these signatures.

The present study provides another impressive example of one of challenges of low-energy nuclear structure: the difficulty to formulate a consistent description of even the most basic collective modes in the transition from spherical to deformed nuclear shapes. The scissors mode, governed by a delicate interplay of collective and single-particle aspects, remains a unique testing ground of nuclear structure models aiming at this goal.

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